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BY

W. L. BROWN, M.Sc., Stud. Inst. C.E.

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Excerpt Minutes of Proceedings of The Institution of Civil Engineers
Vol. cxxxvii. Session 1898–99. Part iii.
Edited by J. H. T. Tudsbery, D.Sc., Secretary.

LONDON:
Published by the Institution,
GREAT GEORGE STREET, WESTMINSTER, S.W.
[Telegrams: "Institution, London." Telephone, "Westminster, 51."]
1899.

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## SECT. II.—OTHER SELECTED PAPERS.

(*Students' Paper No. 405.*)

# "Elasticity of Portland Cement."[1]

By W. L. BROWN, M.Sc., Stud. Inst. C.E.

THE object of the research described in this Paper was to determine the coefficient of direct elasticity of cement and cement mortars, and its variation with: (1) different kinds of sand; (2) different proportions of sand; and (3) age.

Experiments were made with neat cement and cement mortars composed of three kinds of sand in the proportions of 1 part of sand to 1 of cement; 2 parts of sand to 1 of cement; and 3 parts of sand to 1 of cement. The different kinds of sand used were:—(A) A good ordinary coarse red sand such as usually used for building purposes. (This was well washed before using.) (B) A poor argillaceous fine sand unwashed; not good enough for ordinary building purposes; and (C) Fine Laxey gravel; a very coarse sand such as is used for making concrete lintels, etc.

The experiments were divided into two distinct sets, throughout each of which one kind of cement was used. The first set was made with cement supplied by Messrs. J. B. White Brothers. The second set was made to supplement the first, special attention being paid to the points where that was incomplete; the cement used for this set was supplied by Messrs. Currie & Co., Liverpool.

*Method Adopted.*—The coefficient of direct elasticity was found by measuring the deflection of beams (of neat cement and cement mortars) caused by a known load at the centre. In the first set all, and in the second set nearly all, the beams measured 30 inches between the supports, their total length being 36 inches. All were approximately 2 inches deep by 1 inch wide; but each was carefully gauged after it had set, and the average cross-section taken. The deflections to be measured were small, and the difficulty in measuring them considerable. After a few preliminary experiments the Author decided to use Professor Ewing's form of extensometer. The cement beam was supported horizontally at two points, one

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[1] This Paper was read and discussed at a Students' Meeting on the 17th December, 1897.

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near each end, by brackets resting on an ordinary lathe-bed. The surfaces of the supports on which the beam rested were not flat, but portions of large cylinders so arranged that the surfaces of contact were parallel straight lines at right angles to the length of the beam. Above this beam and upon the same brackets was fixed an idle iron beam, into which a vertical rod was screwed at the centre, and from this the upper part of the extensometer was hung. The lower clip was fastened to a sling which hung at the centre of the specimen beam and carried the rod on which the weights forming the load were suspended. When the load was applied and the specimen deflected, the upper clip carrying the microscope remained stationary; while the centre of the beam, together with the sling and the lower clip moved downwards; this caused the lower clip to turn about its centre, one end remaining stationary while the other, which was heavier, carried the cross-wire in front of the microscope where the deflection was measured. With this arrangement the upper part of the extensometer could be left in position while any number of specimens was placed in position, tested and removed; the lower part could always be left fastened to the sling, and the iron rod on which the weights forming the load were hung could be placed in position and removed after the specimen had been fixed.

*Preparation of Specimens.*—The cement and sand were first measured in the proportions required for the particular beam. These quantities were then filled into a mixer, and after they had been well mixed dry, water was gradually added and the mixing continued, till the mixture became a homogeneous mass, sufficiently damp to be worked, but still comparatively dry. A portion of this was then placed in a mould and thoroughly tamped down; more was constantly added and tamped, care being taken that layers were not formed, until the mould was full, when it was finished off with a trowel and numbered. The moulds were made of yellow pine; they were formed of two pieces 1 inch thick of the requisite shape, being doweled together and screwed down on a flat board. When a beam, having been properly mixed and tamped, was set, one side of the mould was unscrewed and removed, and then the beam was carefully taken out and immersed in water where it was kept, being taken out only from time to time for the purpose of experiment. In order to facilitate the removal of the beam the moulds were always well oiled before using; this had the additional advantage of helping to preserve the timber and preventing it from cracking. In most cases if due care were exercised the beams were removed without much difficulty; but in the first

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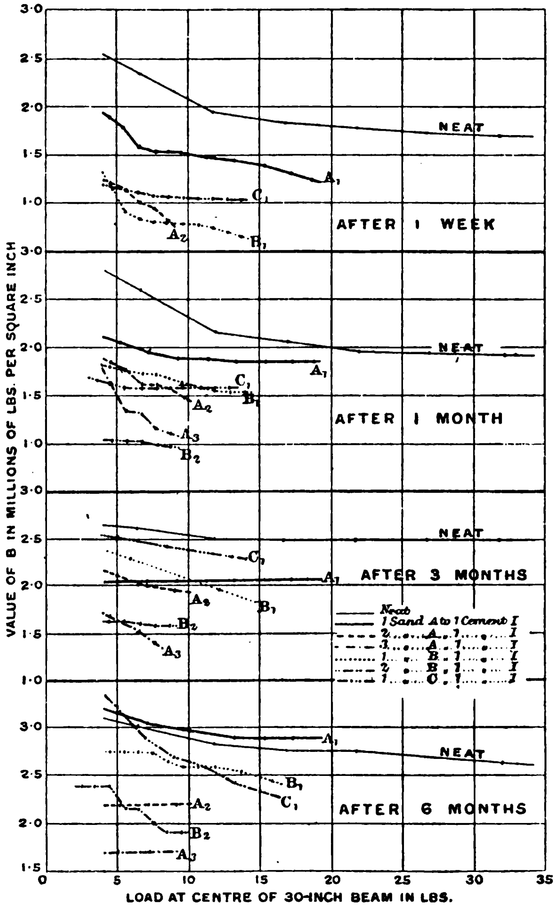
set of experiments of the 3 to 1 beams, only of those made from sand A was there a sufficient number left unbroken to give a reliable average result. It was chiefly for this reason that the second set of tests was undertaken, in which case the 3 to 1 beams were made 24 inches long instead of 36 inches, and remained in the moulds 1 week instead of 1 day or 2 days.

*The Experiments.*—The extensometer was usually found in position before the experiment commenced, being removed only from time to time for the purpose of cleaning either it or the other part of the apparatus. It was found from preliminary experiments that if the load were left on for some time there was a slight settling; most of this took place in the first ½ minute, and after another ½ minute the beam had practically ceased to settle. Consequently, unless some uniform method had been adopted, it would have been impossible to correctly compare either the separate readings of one experiment or the different experiments. An interval of 1 minute was therefore allowed to elapse between the readings. The elasticity is never given for a very small load; an effort was made to counterbalance the initial load, but without success. In the case of very weak beams, however, the initial load was reduced by removing the rod on which the weights were hung, and substituting a light piece of cord strong enough for the load required for these beams. The beam was placed in position by sliding it over one support through the sling and on to the other support; the rod which carried the weights was then hooked on to the bottom of the sling. The extensometer might now be adjusted and its constant taken, and then the experiment might be commenced. A weight of 1 lb. was placed on the rod which hung from the centre of the beam, and after ½ minute a reading was taken; after another ½ minute another lb. was added, and so on, a reading being taken every minute.

It was found that as the load at the centre of the beam increased the deflection per lb. slightly increased, causing the curve to be convex upwards; when the maximum load that was found safe to apply had been reached and the unloading commenced, the recovery was at first only small, but it gradually increased throughout the whole unloading, causing the curve to be concave upwards. After the beam had been unloaded it had not completely recovered itself but had taken a permanent set, the amount of which was very irregular, but generally the older the beam the less was the permanent set. During the unloading when 1 lb. was taken off, the beam suddenly recovered itself a certain amount and continued to recover for a short time; this time effect was more protracted, especially for the earlier readings, than the similar effect which took place during the loading, yet the time between each change of load was the same, consequently the first few readings gave hardly a fair measure of the elasticity.

In all these experiments cross-sections of the beams vary, and consequently the deflections do not give the relative values of the elasticities of the various beams. In order, therefore, to compare the various experiments it was necessary to find some function that was independent of the section and length of the beam; the one that had always been used for other material was Young's

*Fig. 1.*



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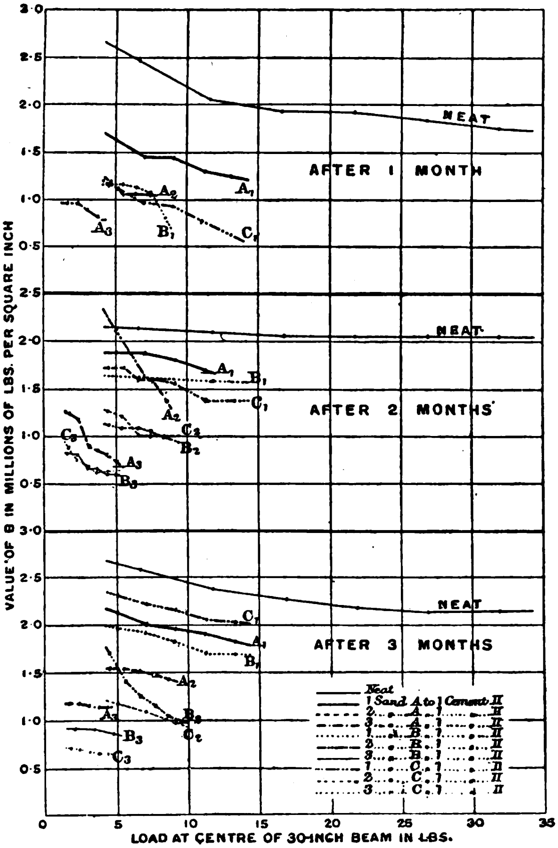
modulus, and although strictly speaking there was no Young's modulus for cement—as the elasticity varied with the loads—a similar function has been taken. This function is always afterwards denoted by B (as it is the measure of the elasticity of cement found by the bending of beams).

*Fig. 2.*



The value of B is found in the same way as Young's modulus is for other materials, *i.e.* from the formula—

$$B = \frac{W L^3}{48 I D},$$

where W = increase of load from one point to the next (usually 1 lb.); D = increase of deflections corresponding to this small increase of load; L = unsupported length of beam (usually 30 inches); I = geometrical moment of inertia of the cross-section about the line at right angles to the direction of the applied force through the centre of gravity of the cross-section; and B is therefore the average value of the coefficient of direct elasticity for a variation of load of 1 lb. at that point of the loading.

*Results.*—Considering first the effect produced by loading. In the two sets of curves, *Figs. 1* and *2*, the average values of B, at different points during the loading of several specimens of the same age and of the same material, are plotted as ordinates; and the loads at the centre of 30-inch beam as abscissas; in the case of the shorter beams the scale of the abscissas has been reduced in

BEAM NO. IV; DISTANCE BETWEEN SUPPORTS, 30 INCHES; EXTENSOMETER CONSTANT, 4,800; INITIAL LOAD, 4 LBS.; NEAT CEMENT II; AGE, 8 WEEKS.

| Load. | Reading On. | Difference. | Difference per Lb. (from Curves). | E. | Reading Off. | Difference. | Difference per Lb. (from Curves). | E. |
|---|---|---|---|---|---|---|---|---|
| 0 | 100·0 | | | | 90·0 | | | |
| 1 | 98·0 | 2·0 | | | 88·0 | 2·0 | | |
| 2 | 96·0 | 2·0 | 2·0 | 2,020,000 | 86·0 | 2·0 | | |
| 3 | 94·0 | 2·0 | | | 84·0 | 2·0 | | |
| 4 | 92·6 | 1·4 | | | 82·0 | 2·0 | | |
| 5 | 90·0 | 2·6 | | | 79·9 | 2·1 | | |
| 6 | 88·0 | 2·0 | | | 78·0 | 1·9 | | |
| 7 | 85·9 | 2·1 | 2·1 | 1,920,000 | 76·0 | 2·0 | | |
| 8 | 83·8 | 2·1 | | | 74·0 | 2·0 | 2·0 | 2,020,000 |
| 9 | 81·7 | 2·1 | | | 72·0 | 2·0 | | |
| 10 | 79·5 | 2·2 | | | 70·0 | 2·0 | | |
| 11 | 77·3 | 2·2 | | | 68·0 | 2·0 | | |
| 12 | 75·1 | 2·2 | | | 66·1 | 1·9 | | |
| 13 | 73·0 | 2·1 | | | 64·1 | 2·0 | | |
| 14 | 70·9 | 2·1 | | | 62·1 | 2·0 | | |
| 15 | 68·8 | 2·1 | | | 60·2 | 1·9 | | |
| 16 | 66·4 | 2·4 | | | 58·2 | 2·0 | | |
| 17 | 64·1 | 2·3 | | | 56·4 | 1·8 | | |
| 18 | 62·1 | 2·0 | | | 54·6 | 1·8 | 1·8 | 2,240,000 |
| 19 | 60·0 | 2·1 | | | 52·9 | 1·7 | | |
| 20 | 57·9 | 2·1 | 2·14 | 1,880,000 | 51·0 | 1·9 | | |
| 21 | 55·7 | 2·2 | | | 49·1 | 1·9 | | |
| 22 | 53·6 | 2·1 | | | 47·7 | 1·4 | | |
| 23 | 51·5 | 2·1 | | | 46·1 | 1·6 | 1·58 | 2,550,000 |
| 24 | 49·3 | 2·2 | | | 44·6 | 1·5 | | |
| 25 | 47·2 | 2·1 | | | 43·1 | 1·5 | | |
| 26 | 45·1 | 2·1 | | | 41·8 | 1·3 | | |
| 27 | 43·0 | 2·1 | | | 40·2 | 1·6 | | |
| 28 | 41·0 | 2·0 | | | 39·0 | 1·2 | 1·26 | 3,200,000 |
| 29 | 38·9 | 2·1 | | | 37·9 | 1·1 | | |
| 30 | 36·8 | 2·1 | | | 36·8 | 1·1 | | |

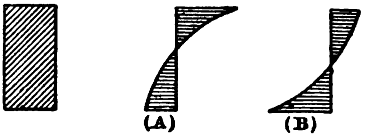
proportion to their unsupported lengths, in order that the bending moment and range of stress may be the same along any ordinate, *i.e.*, the abscissas for 3 lbs. at the centre of a 20-inch beam is the same as for 2 lbs. at the centre of a 30-inch beam.

These curves show that as the load is applied the value of B decreases, *i.e.*, as the range of stress is increased the average value of the coefficient of direct elasticity throughout that range decreases. This at first seems to show that the absolute value of the coefficient of direct elasticity decreases as the stress increases positively. Although this may be so, it does not follow, as will be seen from the following. As the elasticity is not constant stress is not proportional to strain, *i.e.*, the relation $F = PS$, where $F$ = stress, $S$ = strain, and $P$ is a constant, no longer holds. If it is assumed that—

$$F = PS + QS^2 + RS^3 + \cdots\cdots$$

gives the relation between stress and strain, it is impossible to wholly determine the value of the constants. This is not obvious, but can easily be seen for a simple example. Take the case when the relation between stress and strain is expressed by $F = PS + QS^2$. Draw a curve, *Figs. 3*, in which the abscissas represent the stress at every point in some particular cross-section. If the abscissas in (A) represent the stress at every point when Q is positive, then the abscissas of (B) represent them when Q is negative. Now the moment of resistance of a cross-section when the stresses are as in (B) is exactly the same as when they are as in (A). Hence whether $F = PS + QS^2$ or $F = PS - QS^2$ expresses the relation between stress and strain the moment of resistance is the same for the same deflection. But $F = PS + QS^2$ signifies that as F increases positively the elasticity increases; and $F = PS - QS^2$ signifies that when F increases positively the elasticity decreases. Therefore, although the value of B may decrease as the load at the centre of the beam is increased, the coefficient of direct elasticity may either increase or decrease as the stress becomes greater positively. Hence, though the value of B from point to point shows how the beam bends, it does not give the variation of the coefficient of direct elasticity. To obtain the practical results, consider the loading curve as straight; and, taking the total load and total deflection to calculate the

*Figs. 3.*



value of the coefficient of elasticity, this gives the average value of the coefficient of direct elasticity between the extreme limits of stress obtained in each experiment. Such values are tabulated in Table I of the Appendix, from which it appears that:—(1) The value for neat cement is greater than for cement-mortars; (2) The larger the proportion of sand present the less is the value; (3) The quality of the sand has decided effect but not a very considerable one; (4) The value of the elasticity increases with age to a considerable extent. Table II gives for unloading the average values of the elasticity for the different materials at different ages. From this we see that the variation of the elasticity is similar during the unloading to what it is during loading, but its value is higher owing to the permanent set. Table III gives the average value of the permanent set expressed as a percentage of the whole deflection for each kind of material at various ages.

The advisability of investigating the subject having been pointed out by Sir Benjamin Baker,[1] Past-President, this research was carried out by the Author, at the University College, Liverpool, whilst a Student of Professor H. S. Hele-Shaw, LL.D., M. Inst. C.E., to whom he is greatly indebted for the facilities afforded him.

The Paper is accompanied by the entire set of the records of the experiments described, and by plotted curves, from a selection of which the Figures in the text have been prepared.

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[1] Minutes of Proceedings Inst. C.E., vol. cxv. p. 83.

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# APPENDIX.

Table I.—Mean Value of B during the Loading (at Different Ages).

*Set I.*

| Material. | 1 Week. | 1 Month. | 3 Months. | 6 Months. |
|---|---|---|---|---|
| Neat | 1,850,000 | 2,050,000 | 2,530,000 | 2,800,000 |
| Sand A— | | | | |
| 1 to 1 | 1,450,000 | 1,860,000 | 2,060,000 | 2,980,000 |
| 2 to 1 | 1,010,000 | 1,620,000 | 2,050,000 | 2,210,000 |
| 3 to 1 | .. | 1,310,000 | 1,570,000 | 1,710,000 |
| Sand B— | | | | |
| 1 to 1 | 790,000 | 1,630,000 | 2,000,000 | 2,680,000 |
| 2 to 1 | .. | 1,000,000 | 1,640,000 | 2,100,000 |
| Sand C— | | | | |
| 1 to 1 | 1,060,000 | 1,590,000 | 2,410,000 | 2,720,000 |

*Set II.*

| Material. | 1 Month. | 2 Months. | 3 Months. |
|---|---|---|---|
| Neat | 1,910,000 | 2,070,000 | 2,280,000 |
| Sand A— | | | |
| 1 to 1 | 1,390,000 | 1,810,000 | 1,960,000 |
| 2 to 1 | 1,070,000 | 1,610,000 | 1,520,000 |
| 3 to 1 | 910,000 | 960,000 | 1,180,000 |
| Sand B— | | | |
| 1 to 1 | 1,050,000 | 1,610,000 | 1,830,000 |
| 2 to 1 | .. | 1,060,000 | 1,270,000 |
| 3 to 1 | .. | 690,000 | 920,000 |
| Sand C— | | | |
| 1 to 1 | 880,000 | 2,120,000 | 2,140,000 |
| 2 to 1 | .. | 1,090,000 | 1,120,000 |
| 3 to 1 | .. | 720,000 | 690,000 |

### TABLE II.—AVERAGE VALUE OF THE COEFFICIENT OF DIRECT ELASTICITY AS THE LOAD IS TAKEN OFF.

*Set I.*

| Material. | 1 Week. | 4 Weeks. | 8 Weeks. | 12 Weeks. | 24 Weeks. |
|---|---|---|---|---|---|
| Neat . . . . . | 2,670,000 | 2,980,000 | .. | 3,430,000 | 3,680,000 |
| Sand A— | | | | | |
| 1 to 1 . . . . | 1,870,000 | 2,590,000 | .. | 3,150,000 | 3,350,000 |
| 2 to 1 . . . . | 1,370,000 | 2,080,000 | .. | 2,610,000 | 2,770,000 |
| 3 to 1 . . . . | 1,610,000 | .. | .. | .. | 2,110,000 |
| Sand B— | | | | | |
| 1 to 1 . . . . | 1,220,000 | 2,110,000 | .. | 2,570,000 | 2,830,000 |
| 2 to 1 . . . . | .. | 1,510,000 | .. | 2,180,000 | 2,490,000 |
| Sand C— | | | | | |
| 1 to 1 . . . . | 1,680,000 | 2,720,000 | .. | 2,860,000 | 2,980,000 |
| *Set II.* | | | | | |
| Neat . . . . . | .. | 2,060,000 | 2,580,000 | 2,780,000 | .. |
| Sand A— | | | | | |
| 1 to 1 . . . . | .. | 2,170,000 | 2,630,000 | 2,550,000 | .. |
| 2 to 1 . . . . | .. | 1,550,000 | 1,990,000 | 1,900,000 | .. |
| 3 to 1 . . . . | .. | 1,270,000 | 1,670,000 | 1,340,000 | .. |
| Sand B— | | | | | |
| 1 to 1 . . . . | .. | 1,610,000 | 2,070,000 | 2,020,000 | .. |
| 2 to 1 . . . . | .. | .. | 1,380,000 | .. | .. |
| 3 to 1 . . . . | .. | .. | 1,000,000 | 1,100,000 | .. |
| Sand C— | | | | | |
| 1 to 1 . . . . | .. | 1,040,000 | 2,310,000 | 2,500,000 | .. |
| 2 to 1 . . . . | .. | .. | 1,390,000 | 1,760,000 | .. |
| 3 to 1 . . . . | .. | .. | 720,000 | 950,000 | .. |

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TABLE III.—PERMANENT SET EXPRESSED AS A PERCENTAGE OF THE TOTAL DEFLECTION.

*Set I.*

| Material. | 1 Week. | 4 Weeks. | 8 Weeks. | 12 Weeks. | 24 Weeks. |
|---|---|---|---|---|---|
| Neat . . . . . | 27 | 28 | .. | 23 | 20 |
| Sand A— | | | | | |
| 1 to 1 . . . . | 20 | 26 | .. | 34 | 17 |
| 2 to 1 . . . . | 25 | 21 | .. | 24 | 14 |
| 3 to 1 . . . . | .. | 22 | .. | 20 | .. |
| Sand B— | | | | | |
| 1 to 1 . . . . | 33 | 21 | .. | 14 | 9 |
| 2 to 1 . . . . | .. | 35 | .. | 24 | 15 |
| Sand C— | | | | | |
| 1 to 1 . . . . | 53 | 34 | .. | 16 | 17 |
| *Set II.* | | | | | |
| Neat . . . . . | .. | 17 | 14 | 10 | .. |
| Sand A— | | | | | |
| 1 to 1 . . . . | .. | 35 | 27 | 18 | .. |
| 2 to 1 . . . . | .. | 29 | 17 | 19 | .. |
| 3 to 1 . . . . | .. | 20 | 25 | 23 | .. |
| Sand B— | | | | | |
| 1 to 1 . . . . | .. | 25 | 22 | 16 | .. |
| 2 to 1 . . . . | .. | .. | 27 | .. | .. |
| 3 to 1 . . . . | .. | .. | 32 | 22 | .. |
| Sand C— | | | | | |
| 1 to 1 . . . . | .. | 21 | 8 | 15 | .. |
| 2 to 1 . . . . | .. | .. | 27 | 23 | .. |
| 3 to 1 . . . . | .. | .. | 19 | 22 | .. |

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